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A REVIEW OF GLOBAL NAVIGATION SATELLITE AND AUGMENTATION SYSTEMS

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Abstract

The importance and application of global navigation satellite systems (GNSS) has never been greater; there is increasing demand for both commercial and government projects; indeed, owning and operating a GNSS facility has become a matter of national esteem. This article reviews some of the history that led up to the USA building its benchmark Global Positioning System (GPS) exploiting electromagnetic waves and reviews the progress being made by other nations and regions in constructing accurate navigation positioning systems.

Keywords : Augmentation Systems, Galileo, GBAS, GNSS, Navigation, NSAS, Satellite, SBAS,

INTRODUCTION

Before the United States Global Positioning System (GPS) was created, human kind's quest for accurate navigation system dates back to the requirements for maritime power especially by the Europeans. In the sixteenth century European sailors could determine their approximate positions through longitude and latitude coordinates, however whilst the latitude coordinate had a reasonable level of precision, longitude was more of a guess using dead reckoning procedures; a costly weakness for sailing ships in oceans, which could cause serious deviations in a ship's course and loss of ships in uncharted waters. Realizing the importance of position determination and to reduce

the loss of ships, in 1598, King Philip of Spain offered a fabulous fortune equivalent to millions of pounds today to any person who could discover a way of determining longitude. No one won the prize even though half a century before the offer, Gemma Frisius discovered the scientific principle of using the rotation of the earth as a clock to work out differences in longitude by translating to differences in time and vice versa (Lawal & Chatwin, 2011). No one in Spain or anywhere else at that time could build such a clock and the search for this continued over the next century by governments of Venice and Holland, all in vain and finally by those of England (Act 12 Queen Anne, 8 July, 1714) and France (1716). The English prize amounting to £20,000 (equivalent of millions of Pounds today) was meant for a method accurate to within half a degree of arc (2 minutes of time) or 30 nautical miles (David, 1980).



Fig. 1. Harrison's First Marine Timekeeper (H1). Source: National Maritime Museum

Horology at this time had made considerable advancement; however pendulum clocks, invented by Huygens in 1660, made time measurement possible to a fraction of second, however, they were not usable for determination of longitude at sea; not even its improvement with a coiled spring as a governor or controller in 1675 was considered appropriate or precise enough due to some variations. The same year; 1675, King Charles II founded the Royal Observatory to solve the problem of finding longitude at sea using a competing astronomical method known as the Lunar Distance Method developed by Astronomer Royal, Nevil Maskelyne. Sailors measure the

moon's position in relation to stars and used the moon's position compiled at the Royal Observatory to calculate the time at Greenwich (Davida, 2003 and Donnell, 2002). Isaac Newton in 1721 noted discouragingly on the progress of watchmakers by commenting on various efforts and solutions to the proposal: "It is not to be found at sea by any method by which it is not to be found at land". The challenge continued with all professional clock makers and watch makers until John Harrison of Barrow in North Lincolnshire; an autodidact on clock making used wood for plates and wheelwork instead of the usual brass. His further work on chronometry was believed to be guided by manuscript copy of lectures on natural philosophy by Nicholas Saunderson, Lucasian Professor of Mathematics at Cambridge, they were lent to him by a traveling clergyman who ministered at the local church on Sundays (David, 1980 & Donnell, 2002). In 1735, Harrison's first Marine Timekeeper; H1 as shown in figure 1, was brought to London and displayed to the scientific community and tested in 1736 aboard a ship: Centurion to Lisbon. Other models H2 and H3 followed to improve on requirements set by the Board of Longitude. In 1753, Harrison commissioned London watchmaker John Jefferys to craft a watch from his own designs. The model, H4 was completed and miniaturized to 13 centimeters in diameter and weighed about 1.45kg. After a period of some thirty years of innovative work on various designs and constructions, timepiece H4 was completed in 1759 and tested aboard the ship Deptford, which set sail on 18th November 1761, it was accurate enough to satisfy the set conditions for the prize. After several convincing trials for the Board of Longitude, the honor and recognition for the breakthrough: that a marine chronometer was possible, went to the self-taught genius, Harrison. Another model H5 gave superb performance in a 1772 in a trial conducted by King George III. Intervention by the King himself, as an amateur astronomer and a special Act of Parliament in June 1773 (Lawal & Chatwin, 2011) was required due to the Board of Longitude's skepticism, which was considered inappropriate by the King and other members of the scientific elite. His work, different models, craftsmanship and artistry inspired new solutions; from the escapement device principle at the heart of all mechanical marine chronometers discovered by a Frenchman: Pierre Le Roy; to its improvement and application for production through the work of two English men: John Arnold and Thomas Earnshaw (Davies, 1978; David, 1980 & Donnell, 2002). Other plans and solutions followed such as Captain Robert Wauchope of the Royal Navy time balls tested first at Portsmouth in 1829 (Lan & Steven, 1981). Wauchope persuaded other foreign countries to adopt the establishment of time-signal stations through their embassies in London. In

December 1830, the U.S Navy established a depot of charts and instruments for the purpose of maintaining the Navy's charts and instruments and for the rating of chronometers. After the First World War, radio time signals offered alternative technology for determination of the Greenwich Time and thus longitude at sea. The first manifestation of new technology capable of usurping the super accurate mechanical chronometers occurred in 1904, when the United States Navy began to experiment with the transmission of radio-time signals as an aid to the determination of longitude (Davies, 1978). The challenge for precision continued with Naval Navigation systems, which depends on electromagnetic waves travelling at 300,000,000 m/s, where one microsecond error in a vessel's time will result in 300 metres of navigational error.

The Global Positioning System (GPS) originated from the Navigation System with Timing and Ranging known as NAVSTAR, which was initiated by the Joint Program Office (JPO) of the U.S. Department of Defence (DoD) in 1973. The first GPS satellite was sent into orbit in 1978. Initial Operational Capability (IOC) was reached in July 1993 with 24 satellites, while Full Operational Capability (FOC) was declared on July, 17th, 1995. The primary goals were military but the U.S Congress directed the Department of Defense (DOD) to promote civil use free of charge. As a result, the C/A signal on the L1 carrier was made public but can intentionally be degraded by Selective Availability (SA). The deactivation of the selective availability was stopped on the 2nd May 2000 and the improvement for civilian users went from 100 m to about 20m accuracy. The United States Global Positioning System (GPS) is the benchmark satellite navigation system, it consists of a constellation of satellites in orbit that allow us to determine location and time, thus enabling navigation (tracking) of objects on and above the surface of the earth based on the mathematical principle of trilateration. The GPS system is owned and operated by the United States Air Force (Parkinson & Spilker, 1996; Gergory, 1996; Kowoma, 2009; Dana, 1999; Lawal & Chatwin, 2011).

GLOBAL NAVIGATION SATELLITE SYSTEM(GNSS)

Considering its usefulness in aviation, maritime, public safety and disaster relief, rail, roads and highways, space activities, military operations and defense, surveying and mapping, timing &

synchronization, other powerful nations with strong economies and military power, who do not want to depend on the USA GPS have or are in the process of deploying their own independent navigation satellite system. The Russian Navigation System is called the Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS), the European Union have created a navigation system called Galileo managed and operated by civilians, it is expected to have full global coverage by 2020. Similarly, the Chinese Navigation Satellite System is named the Beidou Navigation Satellite System, which has started with coverage of China and Asia and is expected to have full global coverage by the year 2020 (Galileo, 2019; Quilan, 2005). Whilst GPS refers to the United States navigation satellite system, the generic term for such a system is: Global Navigation Satellite System (GNSS), this refers to a constellation of satellites in orbit that are capable of offering Positioning, Navigation and Timing (PNT) services, which are owned and operated by a country or region. It means that with a GNSS receiver, you can determine geographic location anywhere in the world. Figure 1 illustrates a typical GNSS with a constellation of satellites around the globe.

Global Navigation Satellite Systems (GNSS)

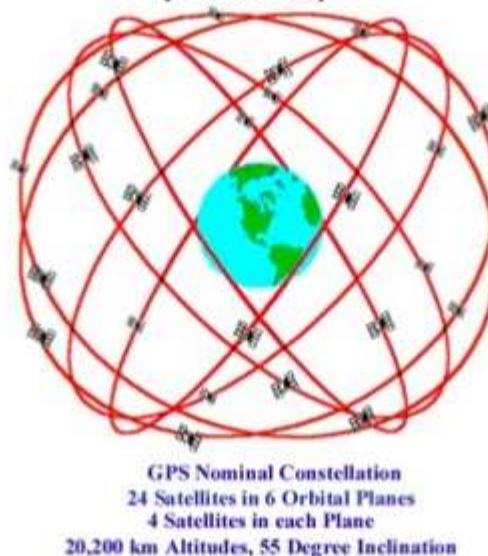

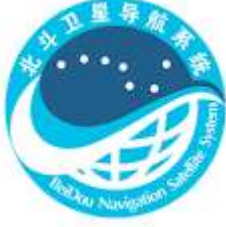


Figure 1. Typical GNSS System with 24 satellites in constellation for global coverage (Source: Mahesh, 2014)

Table (1) below provides an overview of the various Global Navigation Satellite Systems with partial or global coverage, the system operators and owners are indicated.

Table 1: Overview of Global Navigation Satellite Systems (GNSS)

System	Owner (Country/Region)	GNSS System Logo	Operator	Initiation and Current Operational Capability
GPS	United States of America (USA)		United States Air Force	Initiated 1973 and achieved Full Operational Capability (FOC) in 1995.
GLONASS	Russian Federation		The Roscosmos State Corporation	Initiated in 1975 with Full operational capability (FOC) in 1996. 2011 (Restarted Modernization)
GALILEO	European Union (EU)		European GNSS Agency (GSA)	Initiated by European Commission (EC) in 2000 and reached Initial Operational

				<p>Capability (IOC) in 2014.</p> <p>Galileo Initial Services were achieved in 2016. Full operational capability with global coverage is expected by the year 2020.</p>
BeiDou Navigation Satellite System (BDS).	People's Republic of China (PRC)		The China National Space Administration (CNSA)	<p>Initiated in 1990s. Regional System declared operational in 2011. Global coverage with Full operational Capability is expected by year 2020.</p>

GNSS systems are constantly being modernized from legacy systems to newer generations with improved services and being made compatible and interoperable with each other so that receivers can use two or more constellations (i.e GPS +GLONASS, or GPS +Galileo+ GLONASS). This improves performance and services provided the receivers are capable of receiving the different GNSS signals (Lawal & Chatwin, 2011, 2017, 2019; Gao & Enge, 2012; Reza & Buehrer, 2012).

AUGMENTATION SYSTEMS

An augmentation system is any system that aids a Global Navigation Satellite System (GNSS) in providing further accuracy, integrity, availability and other forms of improvement to positioning, navigation, and timing for professional use and application in survey or critical sectors that involves safety of life (SOL) i.e aviation and thus requiring verified performance with integrity.

Augmentation can be ground-based (Ground-Based Augmentation System, (GBAS)) or a Satellite-Based Augmentation System (SBAS).

Good examples of ground-based systems utilizing GNSS are:

- i. DGPS (Differential GPS) is generally a system that provides positional corrections to GPS signals using a fixed, known position to improve performance and eliminate pseudo-range errors.
- ii. Localization of GNSS signals at Very High Frequency (VHF) around Airport locations to increase aviation safety and operations during approach and departure.
- iii. Continuously Operating Reference Stations (CORS) offering precise positioning services to the centimeter and sub-centimeter level for professional use in survey and national spatial reference scenarios.

SBAS using a Geostationary Communication Satellite are ubiquitous and cover a wide area compared to a GBAS system. Global and Regional satellite-based augmentation systems are part of efforts geared towards GNSS integrity enhancement techniques, with enhanced accuracy service guarantee and improved performance, integrity of information, differential corrections using geo-satellites and ground-related infrastructure. SBAS aims to improve accuracy and reliability of GNSS information by correcting signal measurement errors, providing information about the integrity of the same signals and retransmitted over a large service area via a geostationary satellite capable of covering one-third of the earth's surface, see figure (3). Global coverage can be achieved using three geostationary satellites, see figure (4), except for the extreme polar regions beyond 80 degrees latitude, which is invisible from the reach of a geostationary

satellite orbit about 36,000km away from the earth surface. However, inclined geostationary satellites at some degrees to the equator or geosynchronous satellites are visible to the polar regions geometrically, hence, with additional satellite resources it is simple to cover the polar regions.

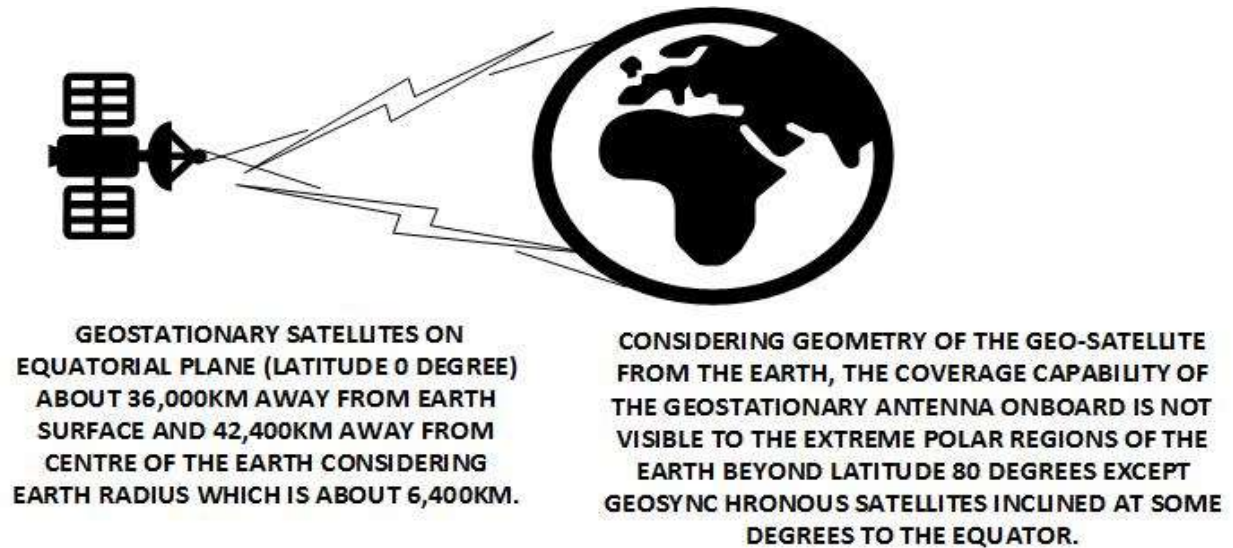


Figure 3: Simple illustration of coverage capability of geostationary satellite up to one-third of the earth's surface.

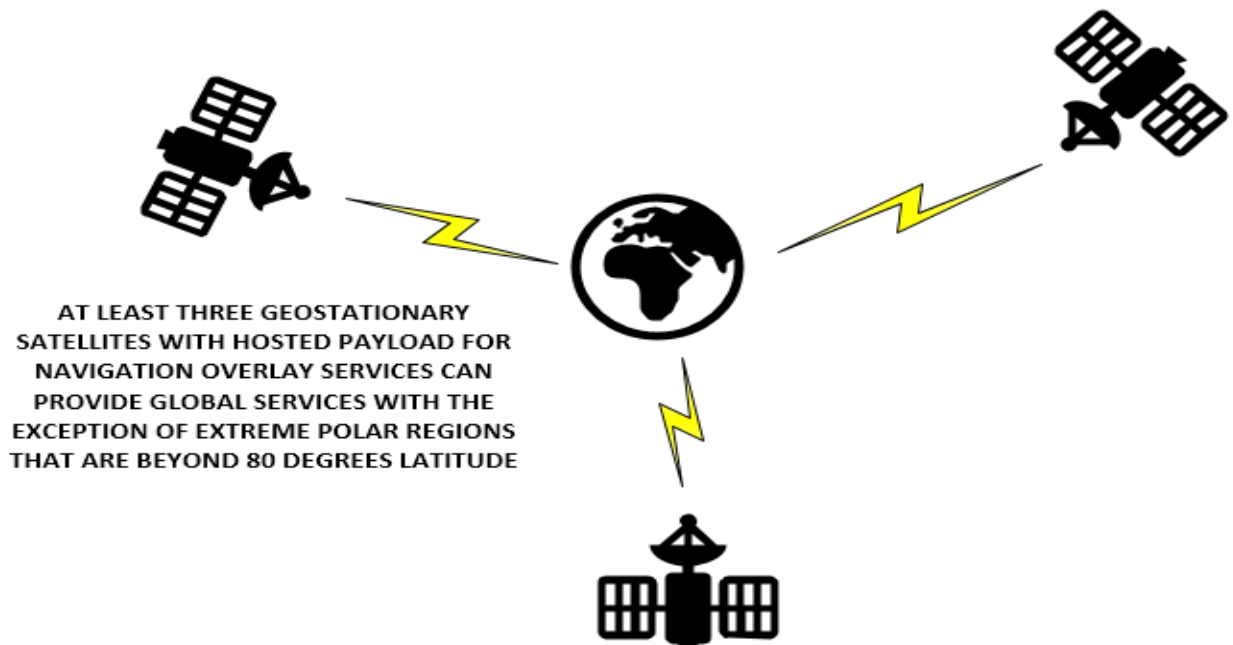


Figure 4: Illustration of use of Geostationary Satellites for Total Global Coverage.

For instance, using the United States Spaced Based Augmentation System as an example, rather than providing a Ground-Based Augmentation System for operations in every airport, the United States deployed a Wide Area Augmentation System (WAAS) on a geostationary satellite that is extremely accurate for civil aviation. Before WAAS, the U.S. National Airspace System (NAS) did not have the potential to provide horizontal and vertical navigation for approach operations for all users at all locations but with WAAS, this capability is a reality, it provides service for all classes of aircraft in all phases of flight - including en-route navigation, airport departures, and airport arrivals, meteorological conditions and more (Carlos, 2016).

Below are a number of regional and country wide Satellite-Based Augmentation Systems (planned, operational and expanding):

- i. USA: Wide Area Augmentation System (WAAS), expanded to Canada as CWAAS and planned expansion to South America.
- ii. Europe: European Geostationary Navigation Overlay System (EGNOS) with reach to the North African region.
- iii. China: Chinese Satellite Navigation Augmentation System (SNAS).
- iv. Japan: MTSAT Satellite Augmentation System (MSAS).
MTSAT, which means: Multi-functional Transport SATellite.
- v. India: GPS-Aided Geo-Augmented Navigation (GAGAN).
- vi. Russian Federation: System Differential Correction and Monitoring (SDCM).
- vii. AFRICA: Nigerian Satellite Augmentation System (NSAS): First with Nigeria

Aside from wider coverage, the additional value-added that SBAS provides can be assessed using four criteria:

- Accuracy: the difference between a receiver's measured and real position, speed or time;
- Integrity: a system's capacity to provide a threshold of confidence and in the event of an anomaly in the positioning data, to provide an alarm.
- Continuity: a system's ability to function without interruption.
- Availability: the percentage of time a signal fulfils the above accuracy, integrity and continuity criteria.

TYPICAL EXAMPLES OF SATELLITE-BASED AUGMENTATION SYSTEMS (SBAS) FOR BOTH AVIATION AND NON-AVIATION SECTORS

A good example of SBAS designed to serve both the Aviation and non-aviation sector is the Australian/New Zealand 2nd Generation SBAS project, which is currently a program (GMV News, 2017). GMV of Spain in conjunction with Lockheed Martin of the USA started a two-year collaborative project with Geoscience Australia (GA) of Australia and New Zealand Cooperative Research Centre for Spatial Information (CRCSI) for the deployment of a satellite positioning augmentation system. The objective of the project is to show the potential benefits of satellite navigation technologies in Australia with integrity and high precision applications.

Early in 2017, the Australian Government formally announced a \$12 million–Australian-Dollar investment over two years with an additional \$2 Million Dollar contribution from the New Zealand Government with 10 industry sector applications beyond Aviation and Maritime. These include: agriculture, construction, medicine, consumer, rail, road and utilities exploiting SBAS (Inside GNSS, 2017)

Australia used a 2nd Generation SBAS testbed system broadcasting in dual frequency multi-constellation (DFMC) with Precise Point Positioning (PPP) corrections integrated into an SBAS service on both L1 and L5 frequency signals.

One of the first trials is at Central Queensland University, Australia, who are testing how SBAS can be used by cattle and sheep farmers to lower costs and improve production. The project tested the construction of ‘virtual fencing’ for strip grazing, and looking at how precise tracking of livestock can be used for early disease detection and more efficient breeding programs as well as how crop health can be improved through more precise irrigation, fertiliser use and pest control (CQUniversity, 2017).

“Satellite-based technology is already used significantly in the aviation and maritime industries, however SBAS provides opportunities to increase the safe and productive use of this technology,” Mr. Darren Chester, Australian Minister for Infrastructure and Transport reiterated. “Automated vehicle and train management systems also provide exciting opportunities for road and rail users in the future” (Dean, 2017).

On the scheduled date of June 1, 2017, the program reached an initial milestone by broadcasting on the L1 legacy SBAS, which broadcasts similar messages to those from the Wide Area Augmentation System (WAAS), EGNOS and NSAS of Nigeria.

“The next big milestone was broadcasting for the first time Dual Frequency Multi-Constellation (DFMC) SBAS using GPS L1/L5 and Galileo E1 and E5a,” Jackson told Inside GNSS on September. “We actually over-achieved and the first broadcast was earlier this week, so we’re pleased.” (Inside GNSS, 2017).

Also, for the first time, Lockheed Martin says it’s broadcasting precise point positioning (PPP) signals from an SBAS satellite on both L1 and L5 frequency signals.

Technology companies GMV, Inmarsat, and Lockheed Martin were all involved in the project. The companies have been involved in implementation of SBAS technology around the world, and are handling the technical components of the testbed (Inside GNSS, 2017a)

As far as the infrastructure within the collaborative project is concerned, Geoscience Australia (GA) has selected GMV for the provision of the processing facilities running the augmentation system, Lockheed Martin (NYSE: LMT) for the signal uplink to the GEO satellite, and Inmarsat (LSE: ISAT) for the SBAS payload in the 4F1 satellite.

Lockheed Martin is an American global aerospace, defence, security and advanced technologies company with worldwide interests formed by the merger of the Lockheed Corporation with Martin Marietta in March 1995, while GMV is a privately-owned technological business group with an international presence. Founded in 1984, GMV offers its solutions, services and products in very diverse sectors such as Aeronautics, Banking and Finances, Space, Defence, Health, Cybersecurity, Intelligent Transportation Systems, Automotive, Telecommunications, and Information Technology for Public Administration and large corporations. GMV of Spain supports client's processes by dint of technologically advanced solutions, providing integrated systems, specialized products and services covering the whole life cycle. These range from consultancy and engineering services up to the development of software and hardware, the integration of turnkey systems and operational backup.

The participants, companies and stakeholders continue to reuse all the experience and background expertise in cutting-edge technology for complete success of the testbed project and program.

Similarly, South Korea are on the verge of deployment of SBAS services. Thales Alenia Space has signed a contract with the South Korean space agency, Korea Aerospace Research Institute (KARI), to supply the ground infrastructure for the agency's satellite navigation system, the Korea Augmentation Satellite System (KASS). KARI, on behalf of the South Korean Ministry of Land, Infrastructure and Transport (MOLIT), will receive the KASS system, which relies on the European Geostationary Navigation Overlay System (EGNOS) developed by Thales Alenia Space as prime contractor for the European Commission (Thales Alenia Space Press, 2016)

The EGNOS system has been operating in Europe since 2009 for Safety of Life (SOL) services, but KASS will enhance the positioning performance provided by the current satellite navigation system GPS and with evolution for the future satellites, Glonass and Galileo. According to KARI, it will ensure integrity and availability of services as well as improve positioning accuracy to within one meter.

The ground infrastructure will initially operate via a relay provided by an existing geostationary satellite, and it will be interoperable with other Satellite Based Augmentation Systems (SBAS) worldwide, which guarantees air traffic safety of planes moving between zones. KARI and Thales Alenia Space will be applying an approach based on partnership, which means that an integrated French-Korean team will be in charge of the project under Thales Alenia Space's management.

South Korea will initially be using KASS to provide aeronautical applications, including SOL services so that it can be used during different flight phases, especially landings. It will eventually extend these services to other applications, including maritime, road and rail.

The NigComSat-1R Navigation (L-band) payload provides a Navigation Overlay Service (NOS). The system augments the Global Navigation Satellite System (GNSS) over Europe and Africa.

Dual user frequencies (L1 and L5 frequencies) over the single L1 frequency was implemented as a hosted payload on the NIGCOMSAT-1R Communication Satellite recognizing its importance and advancement over using just the single L1 frequency capabilities of the previous GNSS and integrating with the GPS constellation modernization with its additional civil signal on the L5 frequency and the Galileo system.

The system functionality is similar to the European geostationary Navigation Overlay Service (EGNOS), where a number of ground reference stations monitor the GPS satellites' signals and provide their observations to one or more Master Control stations (MCS). An augmentation message is then generated by the MCS and two (2) signals, C1 and C5, are transmitted via uplink stations within the uplink coverage areas on the C-band. The navigation payload down converts the C-band signals to L-band, L1 and L5, and broadcast these signals globally to users with messages to improve positioning accuracy with integrity. Figure 5 illustrates the coverage of the C-band uplink signals. The NOS augments the GPS standard positioning service by providing three types of information to users: Ranging information, Differential GPS corrections and Integrity monitoring information (NIGCOMSAT-1R, 2009, Lawal & Chatwin, 2019).

The onboard navigation payload has various component redundancies. It is a dual-channel bent-pipe transponder that down-converts two C-band (C1 and C5) uplink signals from a ground earth station to two downlink signals in the two separate bands, L1 and L5. A 4.0 MHz-wide C1 band uplink channel relays in the L1 downlink channel and allows the transmission of the L1 signal, while a 20.0 MHz-wide C5 band uplink channel relays in the L5 downlink channel and allows transmission of the L5 signal.

Table 2: Downlink Frequency and Polarization of NIGCOMSAT-1R L-Band Payload.

Channel	Frequency (MHz)	Polarization	Bandwidth (MHz)
L1-Downlink	1575.42	RHCP	4
L5-Downlink	1176.45	RHCP	20

The beam from the downlink L-band navigation antenna is global, ensuring that NigComSat-1R is capable of broadcasting to its coverage area, GEO ranging signals and Satellite Based Augmentation System (SBAS) signals through the L1 and L5 frequencies as depicted in Table 2.

The In-Orbit Test (IOT) was used to validate the functional capability of the navigation payload and its readiness for function and purpose. Figure 6 and 7 shows the EIRP results of the re-launched Nigerian Communications Satellite (NIGCOMSAT-1R) in the L1 and L5 signal bands respectively.



Figure 5: The uplink coverage beam of NIGCOMSAT-1R Geo-Navigation Satellite using C-Band Navigation Antenna.

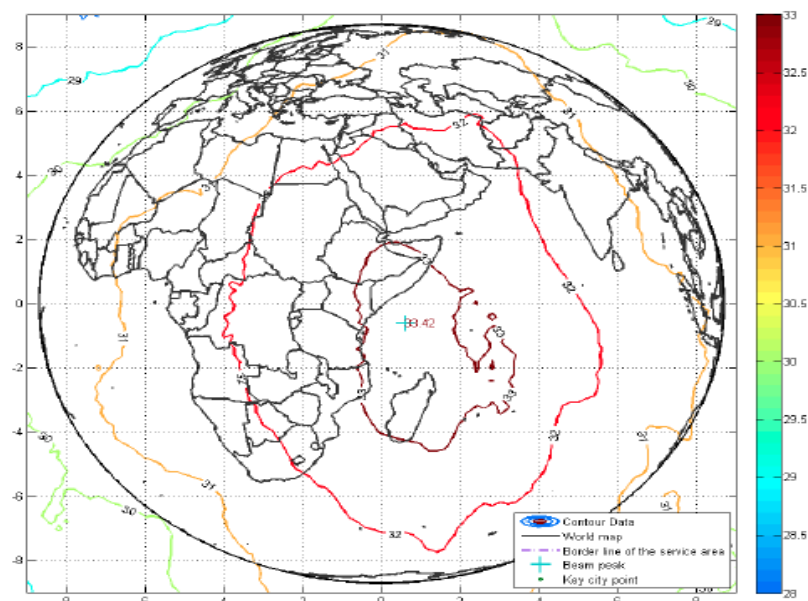


Figure 6: The Downlink coverage beam (L1-Band) of NIGCOMSAT-1R Geo-Navigation Satellite using Dual L-Band Helix Antenna.

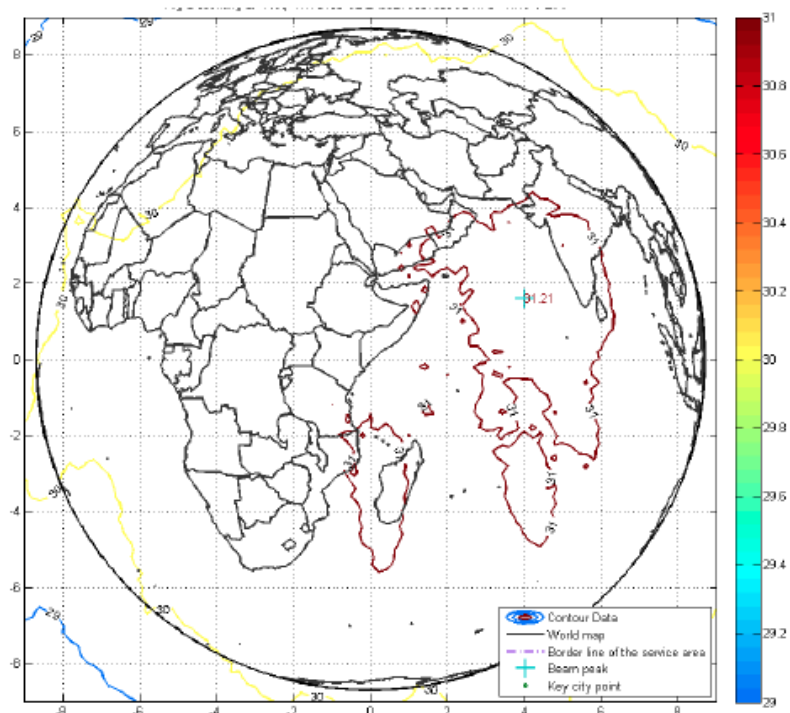


Figure 7: The Downlink coverage beam (L5-Band) of NIGCOMSAT-1R Geo-Navigation Satellite using Dual L-Band Helix Antenna.

A test bed experimentation was conducted in conjunction with partners to validate functional requirements, performance validation of units, sub-systems and systems of both the SBAS payload and ground infrastructure including a pilot project as a demonstration of capabilities and proof-of-concept. The functional requirements covers generation of SBAS messages, coding of SBAS messages in accordance with the Radio Technical Commission for Aeronautics (RTCA) standard, GPS Standard Point Position (SPP), SBAS Precise Point Position (PPP) and SBAS L-band alarm function as well as general performance requirements validation such as coding format, GPS Standard Point Positioning (SPP) Accuracy, SBAS Precise Point Positioning (PPP) etc.

These test results show that the SBAS system operates normally, is stable and meets all the design functions and performance requirements.

Figure 8 shows both the tracking graph and Skyplot of the GNSS and SBAS signal-in-space including the NIGCOMSAT-1R Augmentation Signal on Pseudo Random Noise (PRN) Code 147.

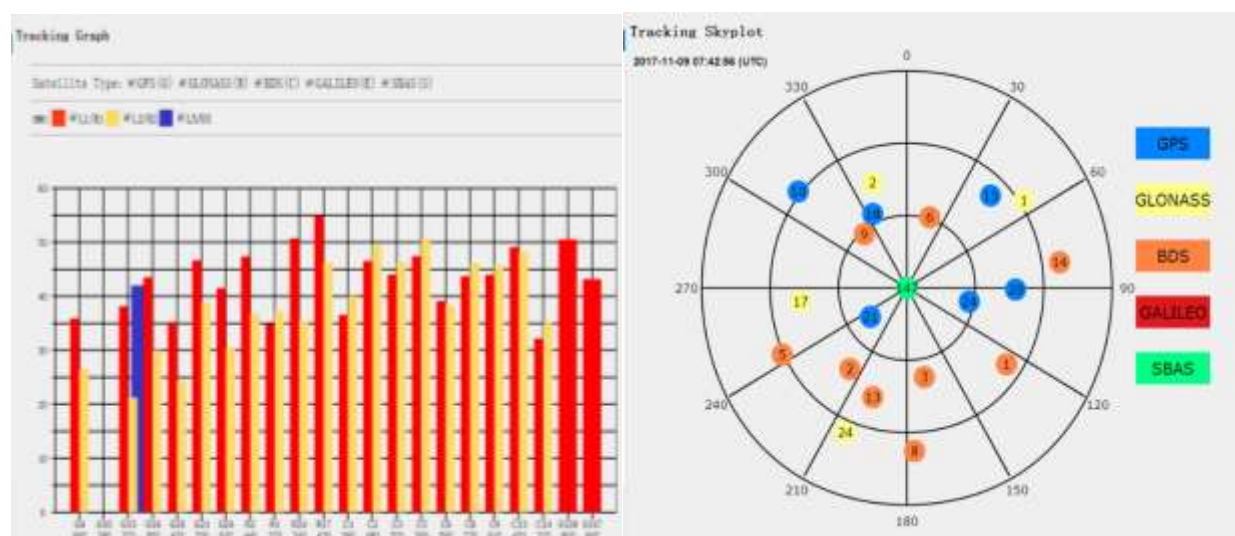


Figure 8: Tracking Graph of GNSS and SBAS signals

Summarising: test results confirm design functionality compliance and performance criteria. Other test results: Continuity Risk Probability $1 \times 10^{-4}/h \sim 1 \times 10^{-5}/h$; Integrity Risk Probability $1 \times 10^{-7}/h$; Reliability: $>99.99\%$ and Clock Estimation Accuracy: $0.3ns$ are good; however, system positioning accuracy will achieve better precision after full deployment of ground infrastructure, after which the aviation sector application tests and functionality will begin.

CONCLUSION

We see a need, especially in civil aviation, for regions without augmentation systems such as: the African continent and South America; for a global SBAS system with worldwide monitoring and reference stations supported by collaborative efforts with a shared sense of ownership through distribution of assets across nations and continents and a new global sovereignty for all parties with augmentation systems. This would eliminate dependency on one GNSS constellation for the aviation and the non-aviation sector with, for a fee, operating companies/organizations as augmentation service providers - creating new sustainable business entities.

The African continent urgently needs such continent-wide augmentation systems with minimum assets (eg monitoring/reference stations) and maintenance budgets - initially concentrating on aviation. The International Civil Aviation Organization (ICAO), a specialized agency of the United Nations, which codifies the principles and techniques of international air navigation and fosters the planning and development of international air transport to ensure safe and orderly growth could spearhead and promote such a global SBAS initiative, with industry stakeholders and interested entities as a service provider, particularly in Africa. It is important to note that commercial aircraft are five times more likely to have an accident flying a non-precision approach than flying a precision approach as reiterated by the Flight Safety Foundation.

Test bed analysis of signal-in-space capability with very high availability has been demonstrated on pseudo random noise code 147, by NIGCOMSAT Ltd in conjunction with partners as a test bed. A series of technical approaches have been used to complete laboratory validations by industry stakeholders, notably by GMV of Spain. Demonstrations by the Australia/New Zealand testbed, for both aviation and non-aviation sectors, on dual frequency multi-constellation (DFMC) with Precise Point Positioning (PPP) have been successful. For non-aviation users this survey shows that the augmentation architecture can be used to support: intelligent transport systems, survey, civil engineering & construction, maritime navigation, unmanned aerial navigation, road & rail transportation sector, supply chain, precision agriculture, utilities and more.

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